Advances in Water Resources 65 (2014) 25–33

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

What mainly controls recession flows in river basins?

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A R T I C L E I N F O

Article history:
Received 5 May 2013
Received in revised form 2 January 2014
Accepted 12 January 2014
Available online 24 January 2014

Keywords:
Recession curves
Power law
Dupuit–Boussinesq aquifer
Active drainage network

A B S T R A C T

The ubiquity of the power law relationship between dQ/dt and Q for recession periods ($-dQ/dt = kQ^{\alpha}$, Q being discharge at the basin outlet at time t) clearly hints at the existence of a dominant recession flow process that is common to all real basins. It is commonly assumed that a basin, during recession events, functions as a single phreatic aquifer resting on a impermeable horizontal bed or the Dupuit–Boussinesq (DB) aquifer, and with time different aquifer geometric conditions arise that give different values of α and k. The recently proposed alternative model, geomorphological recession flow model, however, suggests that recession flows are controlled primarily by the dynamics of the active drainage network (ADN). In this study we use data for several basins and compare the above two contrasting recession flow models in order to understand which of the above two factors dominates during recession periods in steep basins. Particularly, we do the comparison by selecting three key recession flow properties: (1) power law exponent α, (2) dynamic dQ/dt–Q relationship (characterized by k) and (3) recession timescale (time period for which a recession event lasts). Our observations suggest that neither drainage from phreatic aquifers nor evapotranspiration significantly controls recession flows. Results show that the value of α and recession timescale are not modeled well by DB aquifer model. However, the above mentioned three recession curve properties can be captured satisfactorily by considering the dynamics of the ADN as described by geomorphological recession flow model, possibly indicating that the ADN represents not just phreatic aquifers but the organization of various sub-surface storage systems within the basin.
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1. Introduction

Infinitely heterogeneous earth surface and subsurface give rise to complex hydrological flow pathways that can evolve in both space and time, making it difficult to model flow variables using the known laws on water movement, such as Darcy's law. Thus, many of the flow phenomena in natural basins are not yet fully understood, e.g., the old water paradox (e.g., [31]), the scaling of flood peaks (e.g., [23]) and the time of concentration (e.g., [22]). Nevertheless, process understanding is necessary to model more accurately not only streamflows but also many of the environmental parameters such as solute concentration in river channels (e.g., [1,49,50,59,73,74]). Interestingly, despite their complexity, key features of the response of natural basins can be satisfactorily captured by simple conceptual models [3,56]. The simplicity of some general characters of the hydrological response points to the existence of dominant hydrological processes at the basins scale arising from the integration of micro-scale processes [33,39,55]. So for a proper understanding of the hydrological processes, the signatures contained in the hydrological response at basin scale need to be decoded by using suitable analytical or numerical tools. In this regard, appreciable amount of work has been carried out, particularly with respect to flood response (e.g., [30,47,48,50]). Here we focus on the modeling of recession flow curves, which has got relatively less attention.

Though scientific investigation on recession flows dates back as early as Boussinesq [11], a systematic recession flow analysis, to our knowledge, began with the work by Brutsaert and Nieber [16], who expressed $-dQ/dt$ as a function of Q (discharge observed at the basin outlet at time t):

$$-\frac{dQ}{dt} = f(Q) \quad (1)$$

This method essentially eliminates the need of identifying a reference time for a recession event, thereby setting a novel framework for quantifying recession curve characteristics objectively. Brutsaert and Nieber [16] found that $-dQ/dt$ vs. Q curves of a basin typically follow a power law relationship:

$$-\frac{dQ}{dt} = kQ^{\alpha} \quad (2)$$

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http://dx.doi.org/10.1016/j.advwatres.2014.01.001
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Since then many studies have confirmed the presence of the above power law relationship (Eq. (2)) in basins with different sizes and shapes situated across geographical boundaries and climatic zones [4,10,17,18,25,28,29,32,35–38,40,44,53,61,64,66,65]. The question arises thereupon is what causes the seemingly different natural basins to display the same type of power law relationship (Eq. (2)). Is there a distinct dominating flow process common to real basins that operates during recession periods? Brutsaert and Nieber [16] provided an explanation by studying the outflow from a phreatic (unconfined) aquifer resting on a horizontal impermeable bed, i.e., the Dupuit–Boussinesq (DB) aquifer, under different geometric conditions. Another explanation discussed in this study was given by Biswal and Marani [4], who argued that the temporal evolution of saturated channel network gives rise to the power relationship between $-dQ/dt$ and Q. Both the models can, however, be explained through a general mathematical framework [4].

1.1. A common framework for recession flow curve analysis

Rain water stored in the subsurface zones of a hillslope can adopt many possible flow mechanisms to reach surface water bodies. Broadly, ground water flow systems are classified into three categories: local, intermediate and regional [62]. In local flow system water flows to a nearby stream. In regional flow system water particles follow longer (subsurface) flow paths to reach higher order streams. If ground water flow paths are intercepted by one or more topographic highs or lows, it is called an intermediate flow system. Topography and distribution of hydraulic conductivity will decide which flow system dominates in a basin (e.g., [2,14,59]). Furthermore, streams themselves can play a major role during recession events by storing water in their banks and under their beds and releasing it later due to hydraulic gradient (e.g., [24,34,67,69]). Moreover, to make the analysis even more complex, flow paths may undergo changes in both space and time (e.g., [42,75]).

The complex and dynamic nature of flow processes calls for a meaningful conceptualization based on realistic assumptions. At any point of time t, Q can be expressed as a product of flow generation per unit length ($q(t)$) and total length of the channel network contributing flow ($G(t)$) [4]:

$$Q(t) = q(t) \cdot G(t) \tag{3}$$

Differentiating both sides of Eq. (3) with respect to t one finds:

$$\frac{dQ(t)}{dt} = \frac{dq(t)}{dt} \cdot G(t) + q(t) \cdot \frac{dG(t)}{dt} \tag{4}$$

The term $dq(t)/dt \cdot G(t)$ signifies dQ/dt due to aquifer depletion and $q(t) \cdot dG(t)/dt$ due to gradual shrinking of the part of the stream network that is actively draining water at time t or the active drainage network (ADN). In order to examine the relative contributions of the two factors, one can consider two extreme scenarios: (i) where the aquifer dynamics solely controls recession flow and (ii) where the ADN dynamics solely controls recession flow.

1.1.1. DB aquifer model

This model assumes that rectangular shaped phreatic aquifers only generate streamflow in a basin during recession events. Also, it is assumed that the phreatic aquifers in the basin rest on horizontal impermeable beds and are identical everywhere. The phreatic aquifers drain into their nearby stream channels or they follow local flow system. q in this system will be spatially constant, i.e., the role of ADN dynamics can be neglected or $dG(l)/dt \approx 0$. The expression for $Q(t)$ then becomes

$$Q(t) = q(t) \cdot G_0 \tag{5}$$

where G_0 is the total length of the channel network. In effect, this model treats a basin as a 'single' phreatic aquifer resting on a horizontal impermeable bed (DB aquifer). According to Eq. (4)

$$\frac{dQ(t)}{dt} = \frac{dq(t)}{dt} \cdot G_0 \tag{6}$$

$q(t)$ is then modeled by solving the one dimensional Boussinesq's equation under the fully penetrating stream condition and under the assumption that the rate of aquifer recharge is zero (e.g., [16]), also see Fig. 1):

$$f\frac{\partial h}{\partial t} = \psi \frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) \tag{7}$$

where h is the height of water table at distance x and time t, f is the average drainable porosity and ψ is the average saturated hydraulic conductivity of the aquifer. It is assumed that different geometric conditions arise during a recession event, producing $-dQ/dt$ vs. Q curves (Eq. (2)) with different values of α [16,17,38,40,44,68]. Generally three types of geometric conditions are adopted, which have been summarized by Brutsaert and Nieber [16], who also calculated the values of α and k for all the three cases.

The first type of geometric condition applies when the width of the phreatic aquifer (X) is infinite. This condition is assumed to arise in the beginning of a recession event and it lasts for a relatively short period of time. Polubarinova–Kochina [45] found the value of α for this phase to be 3 and

$$k = 1.1334\frac{1}{\psi f H_0^3 G_0^2} \tag{8}$$

where H_0 is H (water table height at $x = X$, see Fig. 1) at $t = 0$. The second type of geometric condition appears when the water table profile can be assumed to be an inverse incomplete beta function. Boussinesq [13] found the value of α for this recession phase to be 1.5 and

$$k = 4.8038\frac{\psi^{0.5} G_0}{f A^{1.5}} \tag{9}$$

where A is area of the basin. This solution is applicable for late recession periods. The third type of geometric condition is characterized by relatively little change in the height of water table ($h(x,t)$, see Fig. 1) in the direction of flow, in which case the Boussinesq's equation (Eq. (7)) can be linearlized [15]. The solution for the linearized Boussinesq's equation was first provided by Boussinesq [12]: $\alpha = 1$ and

$$k = \pi^2 \frac{\psi p H_0 G_0^2}{f A^2} \tag{10}$$

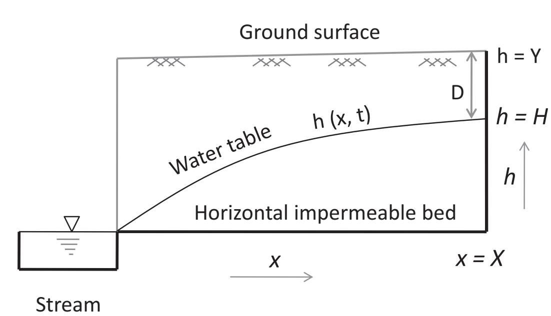

Fig. 1. A graphical illustration of Dupuit–Boussinesq (DB) aquifer (a rectangular unconfined aquifer resting on a horizontal impermeable bed) draining into a fully penetrating stream. There is no recharge into the aquifer, and drainage from the aquifer is expected to reflect recession flows in natural basins.

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